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Responsivity Uniformity Enhancements for Backside-Illuminated Charge-Coupled Devices (BICCDs) by Excimer Laser-Assisted Etching

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We would like to thank Hughes Aircraft Company for supplying test devices for our experiments, and for performing electrical and optical tests on the laser-processed devices. We also extend our thanks to Image Micro Systems (IMS) for allowing us to use their excimer laser micromachining system for some of these experiments.

CONTENTS

1.0 INTRODUCTION

This technical document reports on the research and development of a laser-assisted etching process for texturing sidewalls of backside-illuminated charge-coupled devices (BICCDs), thereby enhancing their responsivity uniformity. It is formatted as a commentary on the compilation of viewgraphs presented at the Optics and Electromagnetic Phenomena Session of the Second Space and Naval Warfare Systems Command (SPAWAR) Research and Development Information Exchange Conference held at the Naval Weapons Center, China Lake, California, on April 2 to 4, 1991.

2.0 ABSTRACT

BICCDs are solid-state electronic imaging devices which read out image charges from wells in an array of pixels. The substrate below the pixel array is typically thinned by chemically etching (100)-oriented silicon using a potassium hydroxide (KOH) etch. The potassium hydroxide anisotropically etches to the (111) crystallographic plane in silicon, leaving smooth sidewalls at an angle of 54.7 degrees to the image plane. This smooth surface acts as a mirror to reflect extraneous light onto the image plane of the BICCD, causing spurious images and reducing the responsivity uniformity (RU) of the devices.

We have developed a noncontact excimer laser-assisted process to promote a chemical reaction between a halocarbon ambient and the silicon. The laser-assisted chemical reaction results in a roughened (textured) surface which behaves as a light sink. The use of a nonreactive ambient allows us to texture the sidewalls of prepackaged and pretested devices. The sidewalls of fully functional BICCD die have been textured in a Freon-115 (chloropentafluoroethane) ambient by directing 5000 pulses with laser fluence of about 0.75 J/cm^2 upon them. The RU of the devices as well as the background level (fat-zero) are dramatically improved.

This abstract has been published (see Ref. 1).

3.0 NOTES AND COMMENTS ON VIEWGRAPHS

In this section, notes or comments are presented on even number pages followed by the viewgraph it pertains to on odd number pages. This format is chosen to most closely replicate the verbal presentation of these results.

3.1 TITLE PAGE

(Viewgraph 1)

Responsivity Uniformity Enhancements for Backside-Illuminated Charge-Coupled Devices (BICCDs) by Excimer Laser-Assisted Etching

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3.2 OUTLINE

(Viewgraph 2)

OUTLINE

I. REVIEW BICCDs and IMAGING PROBLEMS

II. OVERVIEW OF EXCIMER LASER PROCESSING AND NOSC's LASER PROCESSING LAB

III. LASER-ASSISTED ETCHING CHARACTERIZATION

  A. Etch Rate & Critical Parameters

  B. Surface Morphology/Texturing

IV. PROCESSING PROCEDURE and RESULTS

  A. Setup (Die Processing Geometry)

  B. Processing Conditions

  C. Responsivity Uniformity (RU) Results

V. SUMMARY/CONCLUSION

  A. RU Enhancements

  B. Compatibility with Other Processing Techniques

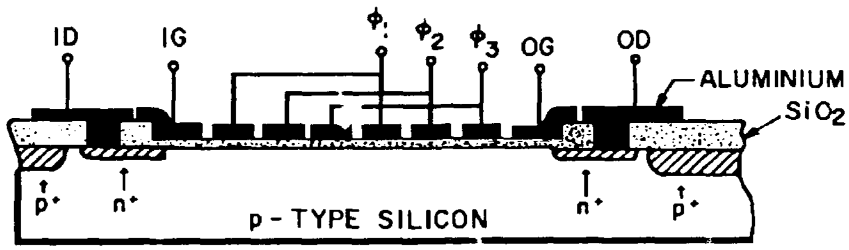
  C. Recent R&D in NOSC Laser Processing Lab

3.3 CHARGE-COUPLED DEVICE

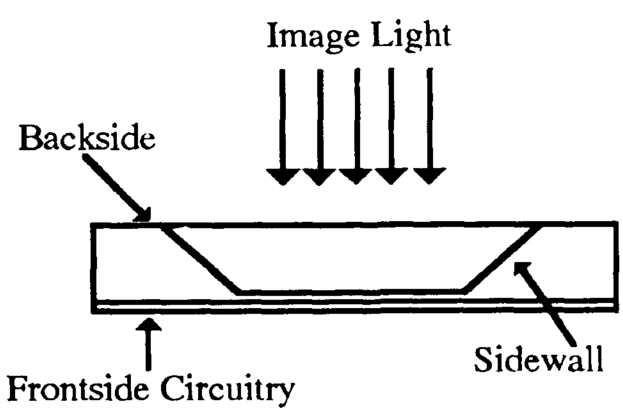
(Viewgraph 3) The upper figure shows a conventional frontside-illuminated charged-coupled device (CCD) (from Ref. 2). This device is fabricated on a bulk silicon wafer nominally 500 μm (20 mils) thick. The gate electrodes, designated by ϕ_i (i = 1,2,3), represent a three-phase clock readout of the CCD pixel array. These electrodes may be fabricated with thin layers of aluminum or polysilicon, but constitute an obstacle for high-performance CCDs, which detect the image light after passing through or around this metallization structure. This design therefore exhibits limitations for low-light-level detection, high resolution, responsivity uniformity, and short-wavelength (blue) response. Imaging of the light from the backside of the wafer is not possible, since all of the visible light is absorbed far from the charge-collection sites beneath the pixel array.

To eliminate the problems associated with imaging through the gate electrodes, BICCDs are fabricated with analagous circuitry on the frontside, but with a thinned area above the pixel array, allowing detection of the image light (see lower figure). This necessitates forming a thin membrane (~10 μm thick) across the active area of the array by wet etching the (100)-oriented silicon wafer with a KOH solution. The KOH anisotropically etches to the (111) crystallographic plane, thereby forming sidewalls at an angle of 54.7 degrees with respect to the image plane. These sidewalls are smooth and highly reflective and allow light to be reflected onto the image plane, causing spurious images.

Charge-Coupled Device (CCD)



Conventional Frontside-Illuminated CCD



Backside-Illuminated CCD (BICCD)

3.4 BICCD IMAGING PROBLEMS

(Viewgraph 4) A three-dimensional plot of the responsivity of a typical BICCD under constant background (fat-zero) illumination is shown. The responsivity in arbitrary units is plotted versus the rows and columns of the array. This technique allows one to examine the responsivity uniformity across the array and the relative background level. Two imaging problems associated with the reflective sidewalls are visible: (1) responsivity nonuniformities characterized by a cruciform (or cross) pattern, and (2) a relatively high background level. The latter was discovered as a potential problem only after the results of this research.

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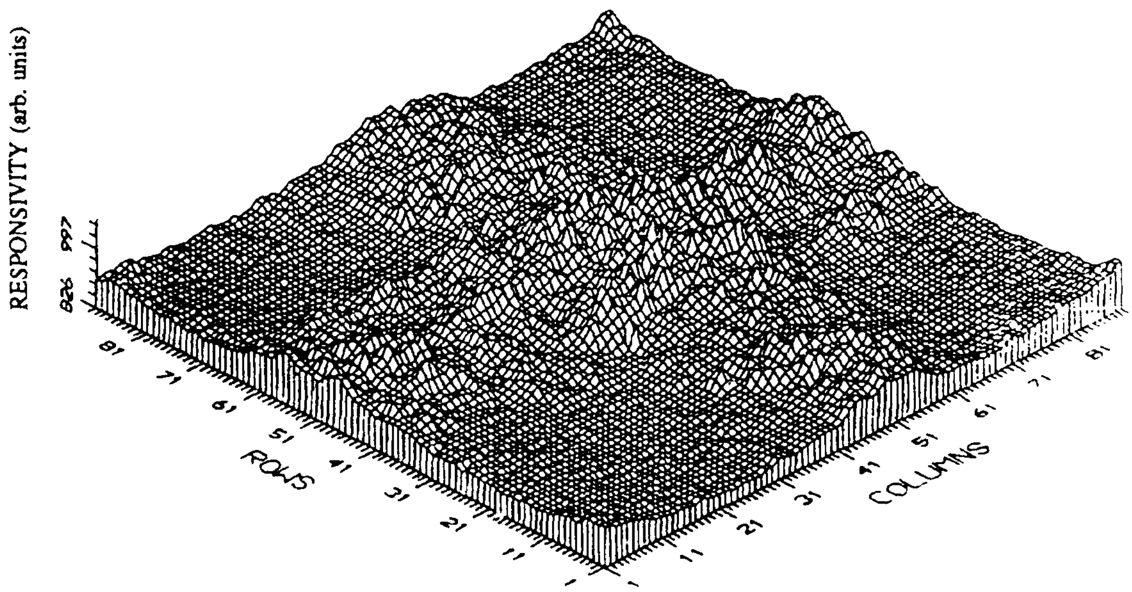
BICCD IMAGING PROBLEMS

1. Responsivity Nonuniformities

2. Elevated Background Level



TYPICAL RESPONSIVITY UNIFORMITY

3.5 GOAL/PROPOSED SOLUTION

(Viewgraph 5) The application of conventional etching or scribing techniques to eliminate scattering from the sidewalls of BICCDs requires the complex masking and handling of thin membranes. Such techniques prove to be low in yield and low in reproducibility and therefore very costly. Alternative system design configurations can be envisioned for the accurate illumination of only the pixel array area of the BICCD. This involves additional apertures or telescopic optics, which increases the overall system complexity and weight. In addition, manufacturability is greatly diminished due to the need for accurate alignment during assembly. Therefore, a novel laser-assisted etching process was proposed as a potential high yield solution to eliminate sidewall scattering.

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GOAL

Eliminate Scattering from Sidewalls onto Array Without Damage to Existing Device

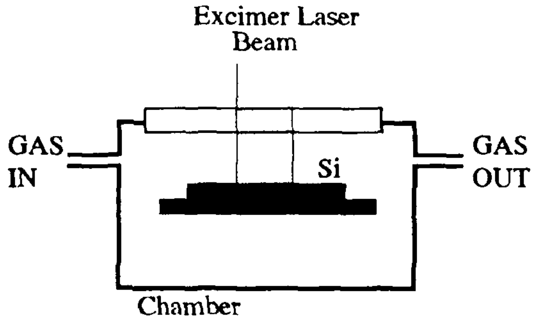
PROPOSED SOLUTION

Laser-Assisted Etching Process To Roughen (Texture) the Sidewalls

3.6 OVERVIEW OF EXCIMER LASER PROCESSING

(Viewgraph 6) The basic process followed in excimer laser-assisted etching requires the introduction of an ambient into a chamber (schematically shown in the viewgraph) with the sample to be etched. The chamber has an inlet for introducing the processing ambient, an outlet for evacuation of gaseous byproducts, and a window for illumination by the laser beam. This process includes: (I) adsorption of the ambient onto the sample, (II) pulsed illumination by the laser, (III) pyrolytic (or thermal) decomposition of the adsorbed ambient, forming halogen radicals and locally melting the silicon, (IV) halogen reaction with the silicon, forming volatile byproducts, (V) desorption of the byproducts, thereby etching about one monolayer of the sample, and (VI) readsorption of the ambient and repetition of the cycle. This process is typically repeated thousands or tens of thousands of times to achieve the desired etch depth.

OVERVIEW OF EXCIMER LASER PROCESSING



I. ADSORPTION OF AMBIENT ONTO SAMPLE (e.g. F_2, Cl_2, NF_3, C_2ClF_5, ...)

II. PULSED ILLUMINATION OF LOCALIZED REGION OF SILICON SAMPLE

III. PYROLYTIC DECOMPOSITION OF ADSORBED GAS, FORMING HALOGEN RADICALS, AND LOCALIZED MELTING OF THE SILICON SAMPLE

IV. HALOGEN REACTION WITH SILICON, FORMING VOLATILE BYPRODUCTS

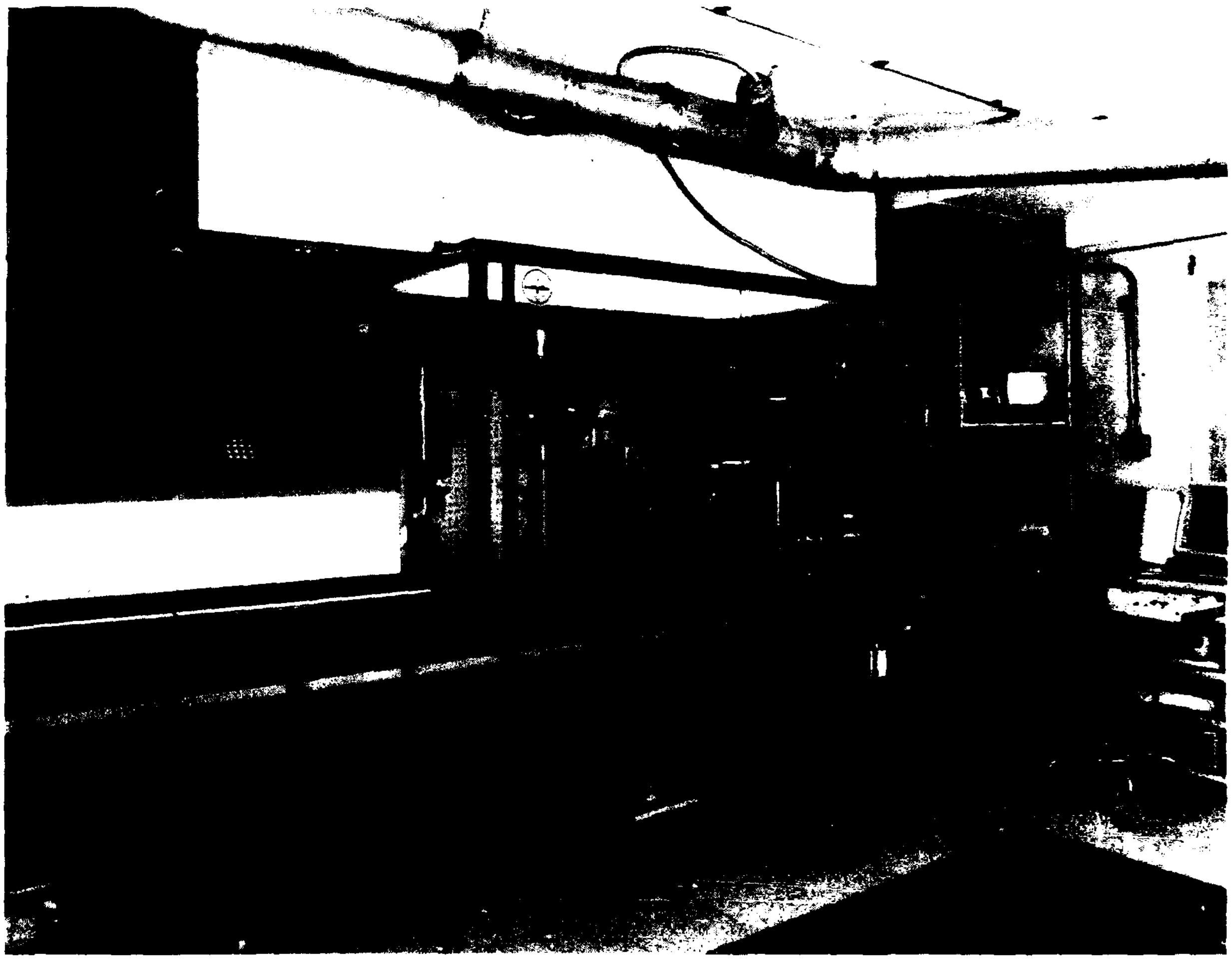
$$Si(liquid) + 4F^*(ads) \rightarrow SiF_4(ads) \rightarrow SiF_4(gas)$$

V. VOLATILE REACTANTS DESORB FROM SAMPLE AND ARE FLUSHED FROM CHAMBER RESULTING IN REMOVAL OF ABOUT ONE MONOLAYER OF THE SILICON SAMPLE

VI. READSORPTION OF THE AMBIENT, AND THE CYCLE REPEATS...

3.7 NOSC LASER PROCESSING LABORATORY

(Viewgraph 7) Shown here is the NOSC laser processing laboratory (circa 1989). At the left is the high-power excimer laser capable of operating throughout the UV wavelength range of 157 to 351 nm, depending on the gain medium. At the center of the photo is the optical path, which contains optics for the homogenization of the laser beam intensity profile, beam profiling optics, and optics to direct the beam onto the sample. A variety of chambers are available for processing individual die or samples as large as wafers 4 inches (100 mm) in diameter. Mass-flow controllers and a corrosive series turbomolecular pumping system are used to control the ambient within the chamber. Computer control and associated in-situ diagnostics are shown at the right in the photo. This system (discussed in detail in Ref. 3) was used to investigate the laser chemistry and characterize the process windows for this research effort.



3.8 LASER-ASSISTED ETCHING CHARACTERIZATION

(Viewgraph 8) The choice of the etching ambient was based on the preliminary research performed for the laser thinning of BICCDs, as discussed in Ref. 3. Halocarbon chloropentafluoroethane (C_2ClF_5) was chosen since it is noncorrosive, has a high etch rate, and results in a roughened (textured) surface. The noncorrosive nature of halocarbons enables the laser processing of fully fabricated BICCD die without damage to any portion. Therefore, the laser process can be carried out only on devices that have passed electrical or optical tests, thereby reducing fabrication costs in handling and processing nonfunctional die.

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LASER-ASSISTED ETCHING: PROCESS CHARACTERIZATION

CHOICE OF ETCHING AMBIENT

Chloropentafluoroethane

C_2ClF_5

Freon-115, Halocarbon-115, ...

3.9 ETCH RATE VS. PRESSURE

(Viewgraph 9) The etch rate versus ambient (chloropentafluoroethane) pressure is shown here for a constant laser fluence (energy density) and at constant temperature. Below about 6 kPa (~50 torr) there is no evidence of etching. At pressures above about 6 kPa, the etch rate increases with pressure, consistent with a Brunauer-Emmett-Teller adsorption mechanism (see Ref. 4). Therefore, the ability to get the etching ambient adsorbed onto the surface is one dominant mechanism in this process.

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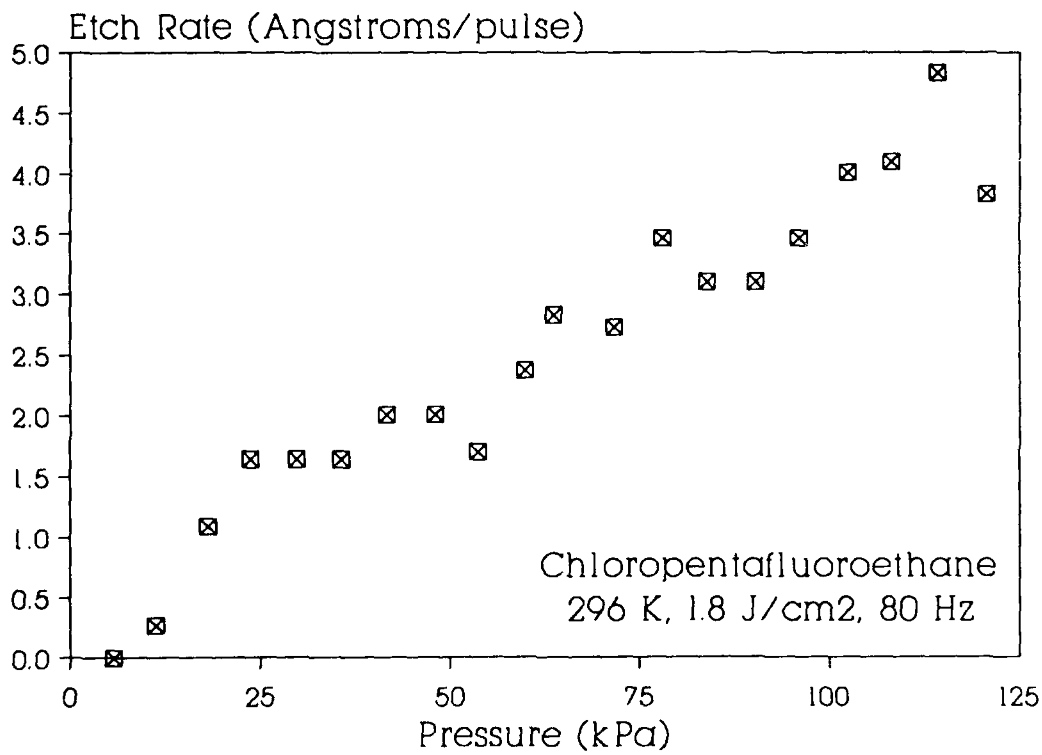
LASER-ASSISTED ETCHING CHARACTERIZATION



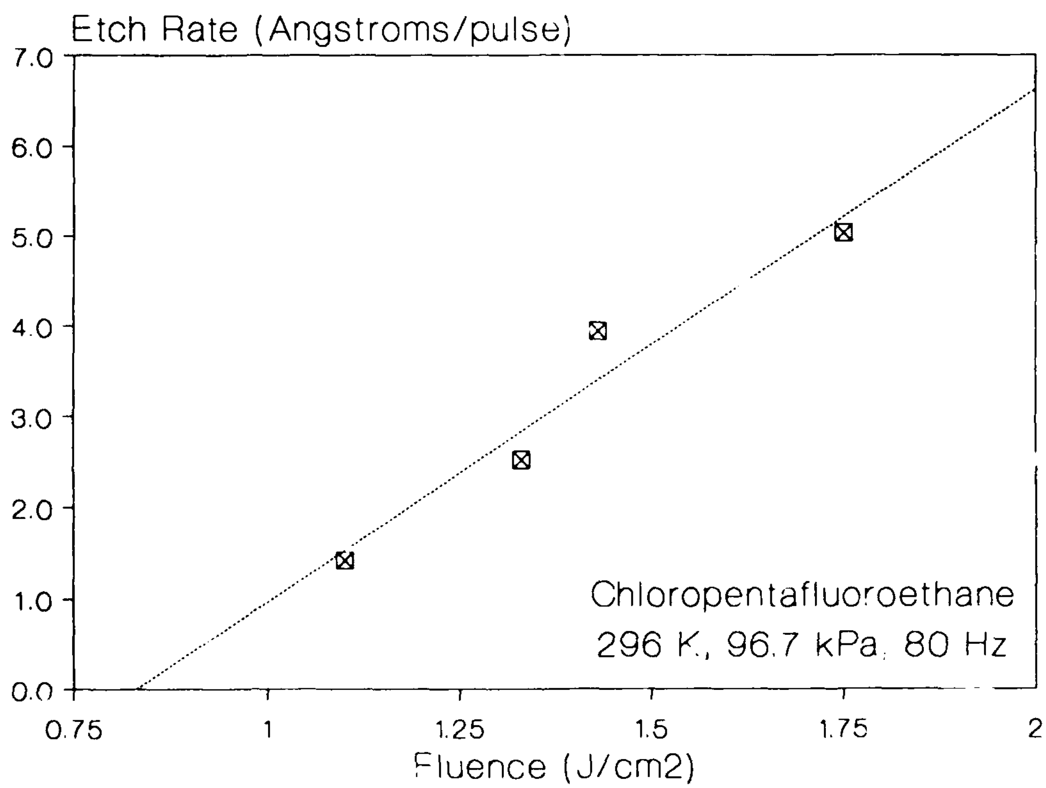
* $P \leq 6$ kPa ... No Evidence of Etching

* $P \geq 6$ kPa ... Etch Rate Increases with Pressure, Consistent with B-E-T Adsorption

3.10 ETCH RATE VS. FLUENCE

(Viewgraph 10) The etch rate versus laser fluence (energy density) is shown at constant ambient (chloropentafluoroethane) pressure and constant temperature. At fluences below that required to melt silicon (about 0.75 J/cm^2), there is no evidence of etching. At fluences above ~2.2 J/cm^2, explosive vaporization of the silicon (ablation) takes place. Within these two extremes in fluence (the melt regime), the etch rate exhibits linear dependence with fluence, consistent with a one-dimensional thermal model. It also suggests that the etching reaction is also governed by desorption of the reaction byproducts, aided by the heating of the surface by the laser.

LASER-ASSISTED ETCHING CHARACTERIZATION



* No Etching Below Melt Fluence

* Etch Rate Has Linear Dependence with Fluence Within the Melt Regime ... Consistent with 1D Thermal Model

* Ablation Threshold ~2.2 J/cm^2

3.11 ADDITIONAL CRITICAL PROCESSING PARAMETERS

(Viewgraph 11) During the characterization of this etching process, we also found that the etch rate is independent of crystal orientation and doping type and concentration. This is consistent with the etching occuring while the silicon is in the molten state.

The etch rate was also found to increase at lower temperatures and decrease at higher temperatures, consistent with the proposed adsorption mechanism since higher sticking coefficients are expected at lower temperature.

The etch rate decreases with an increasing pulse repetition rate due to sample heating by an increased laser duty cycle, and the etch depth increases linearly with the number of laser pulses.

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LASER-ASSISTED ETCHING CHARACTERIZATION

* ETCH RATE IS INDEPENDENT OF CRYSTAL ORIENTATION

* ETCH RATE IS INDEPENDENT OF DOPING TYPE AND CONCENTRATION

* ETCH RATE INCREASES AT LOWER TEMPERATURES AND DECREASES AT HIGHER TEMPERATURES...

  CONSISTENT WITH ADSORPTION MECHANISM

* ETCH RATE DECREASES WITH INCREASING PULSE REP RATE...

  DUE TO SAMPLE HEATING BY INCREASED LASER DUTY CYCLE

* ETCH DEPTH INCREASES LINEARLY WITH NUMBER OF LASER PULSES

3.12 SURFACE MORPHOLOGY

(Viewgraph 12) The surface morphology resulting from the laser etching of silicon in the presence of chloropentafluorethane is shown here. The upper figure is a stylus profilometer trace of a laser-etched crater, about 5 μm deep and 2 mm wide. Large-scale surface variations are due to inhomogeneities in the laser intensity profile. Small-scale roughness is attributed to the etching reaction itself. It is hypothesized that the high diffusivity of the dissociated halogens within the molten silicon prevents recrystallization to a smooth surface, which is obtainable with an inert ambient.

The lower figure shows a scanning electron microscope photograph of a laser etched-crater (about 200 μm deep). The features have a peak-to-valley roughness of about 3 μm and are about 5 μm wide. It has been observed that the feature dimensions increase with an increasing etch depth. This resulting textured surface has a uniform mat finish and visually looks black, i.e., it does not scatter light.

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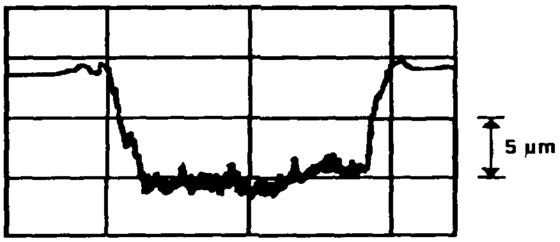
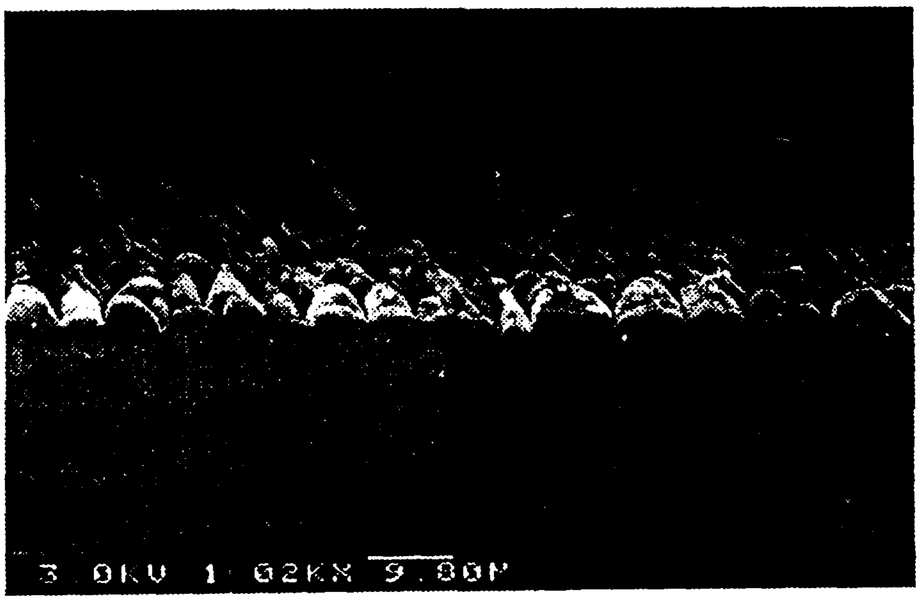
LASER-ASSISTED ETCHING CHARACTERIZATION

SURFACE MORPHOLOGY



Stylus Profilometer Trace of Laser-Etched Crater



Cross-Sectional SEM Photograph of Laser-Etched Surface

3.13 LASER PROCESSING OF BICCDs

(Viewgraph 13)

LASER PROCESSING OF BICCDs:

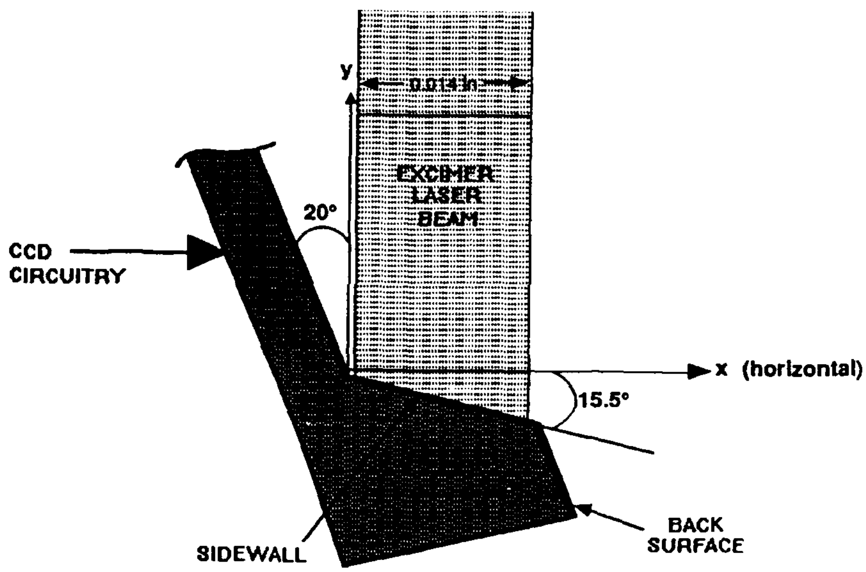
TEXTURING OF SIDEWALLS

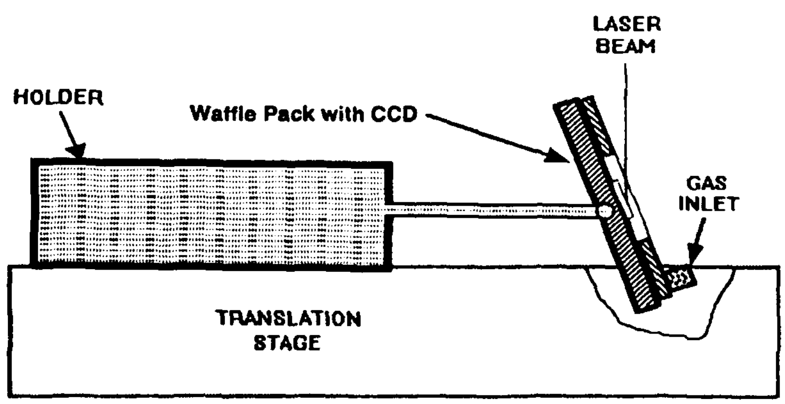
3.14 PROCESSING SETUP

(Viewgraph 14) The experimental setup for laser processing BICCDs is shown in this viewgraph. The upper figure schematically shows the orientation of the die with respect to the incident laser beam. The excimer laser beam is directed so that it only illuminates the sidewall of the BICCD. The die were tilted so that the image plane was 70 degrees from the horizontal to prevent reflected laser light from damaging the antireflective (AR) coating that is normally applied to the imaging array. This AR coating has a damage threshold far below that required to initiate the etching reaction, therefore requiring the use of this configuration.

The lower figure shows a larger view of the entire processing scheme. Individual die are handled only in "waffle packs" specifically designed for protecting these thin membraned, electrostatically sensitive devices. A modified top portion of a waffle pack was created with a gas inlet for the halocarbon ambient and a window for the laser. The waffle pack was mounted in a structure that allowed translation and rotation beneath the laser beam. Not shown in these figures is the excimer laser, beam-delivery system, and gas-handling system required for the processing.

PROCESSING PROCEDURE: SETUP





3.15 PROCESSING CONDITIONS

(Viewgraph 15) The experimental conditions used to laser-texture the sidewalls of the BICCDs were within the processing windows defined earlier; however constraints were imposed by the AR coating on the active area and the optical imaging requirements. As stated earlier, damage to the AR coating required orienting the image plane of the die 70 degrees from the horizontal. There is, however, sufficient specularly scattered light in the first laser pulses to damage the AR coating when high fluences are used, even with a correctly oriented sample. Therefore, using a fluence just above the melt threshold (0.75 J/cm^2 at 248 nm) prevented this damage while still initiating the photothermal chemical reaction.

The optical setup used to direct a homogenized intensity profile with sufficient fluence onto the sidewall was constrained to a 350 µm x 450 µm illuminated area. Therefore, a step and repeat process was carried out following along the sidewalls with about 5000 pulses at each position. An etch depth of about 0.5 µm was required to achieve the desired mat texture. Each die received a total of about 100,000 pulses, corresponding to less than 5 minutes of processing per die (at 400 Hz).

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PROCESSING PROCEDURE: CONDITIONS

WAVELENGTH: 248 nm (KrF)

FLUENCE: 0.75 J/cm^2

ILLUMINATED AREA: 350 μm × 450 μm

PULSE REP RATE: 400 Hz

NUMBER OF PULSES: 100,000 per die

AMBIENT: ~1 Atm flowing Freon-115
(chloropentafluoroethane)

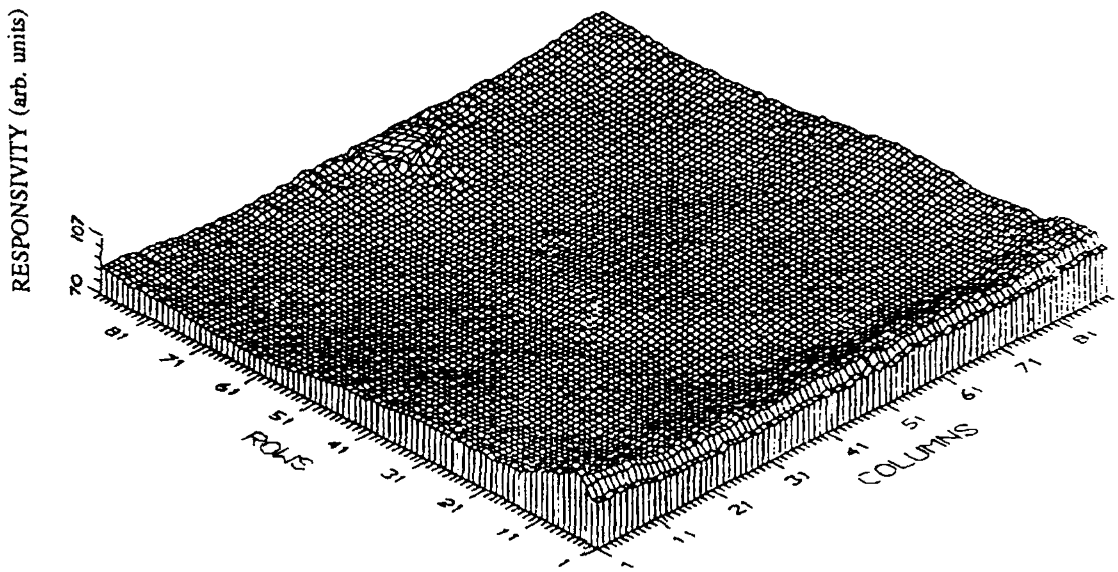
ARRAY ORIENTATION: 70° from horizontal

3.16 RESULTS

(Viewgraph 16) The responsivity uniformity of a laser-textured BICCD is shown in this viewgraph. This exhibits less than 1% responsivity nonuniformities and a ten times lower background level compared to typical BICCDs. Therefore, this process has virtually eliminated the sidewall scattering problem in these devices. In addition, after the processing conditions were determined a 100% processing yield was obtained through the laser process. This is particularly important since large fabrication and testing costs and a great deal of time have been invested in these devices. Therefore, this process shows strong signs as a cost-effective solution as well as a manufacturable process.

RESPONSIVITY UNIFORMITY RESULTS

1. Less than 1% Responsivity Nonuniformities
2. 10X Lower Elevated Background Level
3. 100% Yield on 11 Processed Devices



RESPONSIVITY UNIFORMITY
OF LASER-TEXTURED BICCD

3.17 SUMMARY/CONCLUSION

(Viewgraph 17)

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SUMMARY/CONCLUSION

* LASER TEXTURING OF SIDEWALLS...

  IMPROVES RESPONSIVITY UNIFORMITY (RU) AND DECREASES BACKGROUND LEVEL FOR BICCDs

* TECHNIQUE CAN BE APPLIED TO OTHER NONCONTACT TEXTURING APPLICATIONS

* LASER ETCHING CAN BE PERFORMED WITHOUT DAMAGE TO PARTIALLY OR FULLY FABRICATED DEVICES DUE TO NONCORROSIVE NATURE OF THE HALOCARBON AMBIENT

* LASER-ASSISTED ETCHING IN A HALOCARBON AMBIENT IS COMPATIBLE WITH OTHER LASER PROCESSES AND VLSI PROCESSING TECHNIQUES

3.18 RECENT R&D IN NOSC LASER PROCESSING LAB

(Viewgraph 18)

NOSC

NOSC LASER PROCESSING LAB
RECENT R&D

* Excimer Laser-Assisted Etching of Silicon Using Gaseous and Liquid Ambients for...

  Laser Texturing,
  Thinning Backside of BICCDs,
  Wafer Patterning, and
  Micromachining.

* Excimer Laser Dopant Activation and In-Situ Laser Doping for...

  Bipolar Transistors in Silicon-on-Sapphire,
  Self-Aligned Metal Gate MOSFETs in SOS, and
  Backside Doping of BICCDs.

* Fabrication of Heteroepitaxial Thin Film Ge_XSi_{1-X} Alloys by Excimer Laser Mixing for...

  Graded Base Layer for Heterojunction Bipolar Transistors (HBTs), and
  Near-IR Photodetectors.

* Laser Processing of Thin Film Ferroelectrics for...

  Annealing of Sol-Gel Precursors, and
  Laser Patterning of FE Films.

4.0 REFERENCES

1. Russell, S. D., and D. A. Sexton, "Responsivity Uniformity Enhancements for Backside-Illuminated Charge-Coupled Devices (BICCDs) by Excimer Laser-Assisted Etching," in Second Annual R&D Information Exchange Conference: 2-4 April 1991, NWC-TS-91-22, April 1991, p. 28.

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4. Russell, S. D., and D. A. Sexton, "Excimer Laser-Assisted Etching of Silicon Using Chloropentafluoroethane," in In-Situ Patterning: Selective Area Deposition and Etching, R. Rosenberg, A. F. Bernhardt and J. G. Black, eds., Mater. Res. Soc. Proc., 158, Pittsburgh, PA, 1990, pp. 325-330.

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13 ABSTRACT (Maximum 200 words)

This technical document reports on the research and development of a laser-assisted etching process for texturing sidewalls of backside-illuminated charge-coupled devices, thereby enhancing their responsivity uniformity.

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